Evaluating the Relationship between Soil Texture and Soil Organic Carbon across California Grasslands

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ABSTRACT

Anthropogenic climate change s is irreversible on a multi-century to millennial timescale unless there is a sustained net removal of carbon dioxide from the atmosphere (IPCC AR5 2013). Removal of atmospheric CO_2 occurs by carbon sequestration, a process by which a carbon stock takes up more carbon than it releases. Soil is one such carbon sink; plants naturally sequester carbon through photosynthesis, and some of that C moves into the soil and becomes integrated into the soil carbon pool. The urgency of climate change impels scientists to find ways to enhance and accelerate C sequestration processes. Understanding how much carbon could be stored in soil is essential to understanding the potential for soil carbon sequestration; hence this study aims to understand the relationship between soil properties and soil carbon. As part of a large, multi-stakeholder experiment, I collected soil samples from 16 grassland sites across California and analyzed the soil texture (percent sand, silt, and clay), and soil organic carbon content. Based on the findings, clay content may not provide a good proxy for determining soil carbon in California, but rainfall had a strong positive correlation with carbon. A better understanding of the factors driving C sequestration will allow for enhanced sequestration of atmospheric carbon in a climate change mitigation plan.

KEYWORDS

carbon sequestration, climate change, rangelands, regression

INTRODUCTION

Anthropogenic greenhouse gas emissions are the driving force behind global climatic and environmental changes (Parmesan and Yohe 2003). The primary driver of anthropogenic climate change is the increase in atmospheric carbon dioxide (CO_2), mainly due to human combustion of fossil fuels (IPCC 2013). In order to mitigate the effects of climate change, researchers have looked at methods to remove carbon from the atmosphere for long-term storage elsewhere (Lal 2004, Pacala and Socolow 2004). Oceans are the largest C sink but have already absorbed large quantities of CO_2. Removing atmospheric carbon dioxide and storing the C in biomass has been shown to be effective on a short time scale, but since biomass will eventually be decomposed to CO_2, this sink has a fairly short turnover time (Sabine et al. 2004, Malhi et al. 2002). Soil is the largest terrestrial C sink, storing more C than the atmosphere and vegetation combined, and because most managed land is degraded with respect to C, there is likely a large excess storage capacity in the soil (Post and Kwom 2000).

Soil carbon sequestration has the potential to mitigate the effects of global climate change by storing atmospheric carbon as soil organic carbon (Lal 2004). Plants uptake CO_2 during photosynthesis and convert it into sugars that drive plant growth. The carbon is utilized in different molecules: some will be simple molecules that are later consumed by microbes that return the carbon to the atmosphere as CO_2, and some carbon will be incorporated into more complex soil structures that are protected from microbial decomposition and eventually become integrated into long-term soil carbon pools (Ryals et al. 2015). When the rate of photosynthesis and the movement of carbon into the soil are greater than the rate of decomposition, there is a net gain in soil carbon.

Natural rates of carbon uptake may be too slow to offset any of the effects of climate change. However, management practices can accelerate atmospheric carbon sequestration (Conant et al. 2001), restore soil fertility, reduce erosion and increase soil water holding capacity (Lal 2004, Ryals et al. 2014). Sequestration rates are affected by management practices, such as composting and reducing tillage on grasslands, and soil properties, such as clay content (Ryals and Silver 2013, Montiel-Rozas et al. 2015, Jobbágy and Jackson 2000). Relatively little is known about the relationship between ecosystem variables, soil properties, and the amount of carbon a soil can store. To examine this relationship, I participated in a large field trial, in which compost was applied to grassland sites across the state of California. Prior to compost application, I analyzed soil texture, collected data on ecosystem variables, and measured soil C at each site to discern a relationship between them. This study (and the larger study of which this is part) focuses on grasslands because they comprise 30-40% of non ice-covered land, and previous research has established grasslands as a promising ecosystem for global-scale soil carbon sequestration (Hungate et al. 1997, Jones and Donnelly 2004). If anthropogenic CO_2 emissions were reduced to zero in combination with enhanced soil C sequestration, then there would be a net removal of carbon from the atmosphere, and movement towards reversing the atmospheric CO_2 concentrations to pre-industrial levels. With current emissions, enhancing carbon sequestration buys time to develop more extreme technologies for removing carbon dioxide (Lal 2004).

This project aims to characterize the relationship between environmental variables, soil properties, and soil carbon to better understand the potential of soils to store carbon, and determine if soil carbon can be reliably predicted by environmental variables. Specifically, I examine the relationship between soil texture (clay content) and soil carbon, and also look to other ecosystem variables to explain the variation in soil carbon. Clay particles have a high surface area to volume ratio, so it has been theorized that soils with more clay have more surfaces for chemical interactions and therefore a higher potential for carbon sequestration (Sorensen 1981). Based on this theory, I hypothesize that clay content and soil carbon will be positively correlated. I expect that including other ecosystem variables will improve the predictive power of the regression. Soil moisture content, higher annual rainfall, and higher soil pH all create a healthier growing environment for grasses, so in optimal growth conditions, aboveground and belowground biomass grows larger and more carbon may move from the roots to the soil (Ryals and Silver 2013).

METHODS

Study system

My research took place on 16 grassland sites across California (Figure 1). Generally the sites have a Mediterranean climate with low seasonal rainfall. Most sites are dominated by annual invasive grasses brought to California as forage for grazing. All sites are grazed; cows graze the majority of the sites, and several are grazed by other animals (Appendix A). The sites were selected in collaboration with the National Resources Conservation Service (NRCS), who are interested in testing compost as a potential best management practice for grasslands, and Whendee Silver's lab at UC Berkeley, who designed the field trials to study how compost affects soil carbon sequestration in different ecosystems. My study focused on measuring and analyzing site variables to understand the natural variation of carbon in the study system. Sites were sampled in October 2016, before the seasonal rain.

Figure 1. Field Site Distribution. Map of California counties with blue stars showing locations of field sites.

Data collection

Plot design

As part of the larger study to evaluate the change in carbon sequestration by adding compost to rangelands, we delineated a 60m x 60m study area at each of the 16 grassland sites, and split them in two: one treatment (compost) plot, and one control plot. Within each plot, we placed one transect using a random number generator and took samples at every 10 m along the 50 m transect. (For this study, I used a subset of the transect samples; 3 soil cores from each site, pre-treatment). Using a manual auger, we collected soil samples from 0-10 cm, 10-30 cm, 30-50 cm, 50-80 cm, and 80-100. (For this study, I used only the 0-10 cm samples.) At each site, we dug a 1m x 1m x 1m pit in each plot, and measured bulk density for every 10 cm depth increment. The pit was located using a random number generator. We used a bulk density core with a known volume on the wall of the pit closest to the back of the plot. This method minimizes compaction of the soil, and therefore gives a more accurate assessment of bulk density than simply driving a cylinder into the ground and removing it (Robertson et al. 1999).

Soil texture

To determine soil texture, I analyzed each sample for sand, silt and clay fractions. I ran the soil through a 2 mm sieve to remove rocks, and then weighed 40 grams of soil for each sample. I treated samples with hydrogen peroxide to remove organic matter, and with sodium hexametaphosphate to prevent clumping of soils. I used a Bouyoucos hydrometer to determine sand, silt, and clay fractions according to the procedure created by Gee and Bauder (1986).

Soil carbon

To determine soil organic carbon, I prepared and analyzed samples using a CE Elantech elemental analyzer, which combusts the sample at high temperature and then measures concentrations of C in the gaseous emissions (CO_2, and trace gases containing C) to determine the total amount of organic C in the sample. I prepared the samples by air-drying them, removing roots and organic matter by hand, sieving off particles greater than 2 mm, and homogenizing the soil using a ball grinder (SPEX Sample Prep Mixer Mill 8000D, Metuchen, NJ). Since soil can be very heterogeneous, I ran the samples in duplicate. One of the sites (Kettleman City) was not included in analyses because it tested positive for inorganic carbon and removal of carbonates was not possible in the time frame of this project.

Rainfall

To determine rainfall for each site I used Melissa online database and searched for annual rainfall by zip code of our study sites (Melissa Global Intelligence 2017). I then compared the elevation of the nearest weather station provided by the online database to the elevation of the field site; I included data from weather stations within 100m elevation of the study site to ensure that the rainfall value would be representative of the site. I excluded sites where this was not the case from my study.

Data analysis

In order to determine the relationship between soil carbon and clay content, I ran a simple linear regression analysis between the two variables, after ascertaining that these data passed a test for normality. Soil carbon was measured in g/m^2 of soil; the percent C determined using the elemental analyzer was converted using the bulk density measurement and soil depth. Clay content was measured in percent total soil volume. I also ran a simple linear regression between rainfall and carbon, with carbon in g/m^2 and rainfall in cm. I then ran a multiple regression to determine the influence of rainfall acting in concert with soil clay content on soil carbon. I analyzed the data using R and Microsoft Excel.

RESULTS

Soil clay content correlated with soil organic carbon (SOC) with an r^2 value of 0.19 ($p<0.01$; Figure 2). One site (in Contra Costa County) was removed from all analyses because its carbon content was much higher than all other sites. Its extremely high carbon content is likely due to its location in the Sacramento-San Joaquin delta, where C-rich peaty soils abound. The least squares linear regression equation is

$$C = 43.883x + 1684.8$$

where C is soil carbon content, and x is percent clay content.

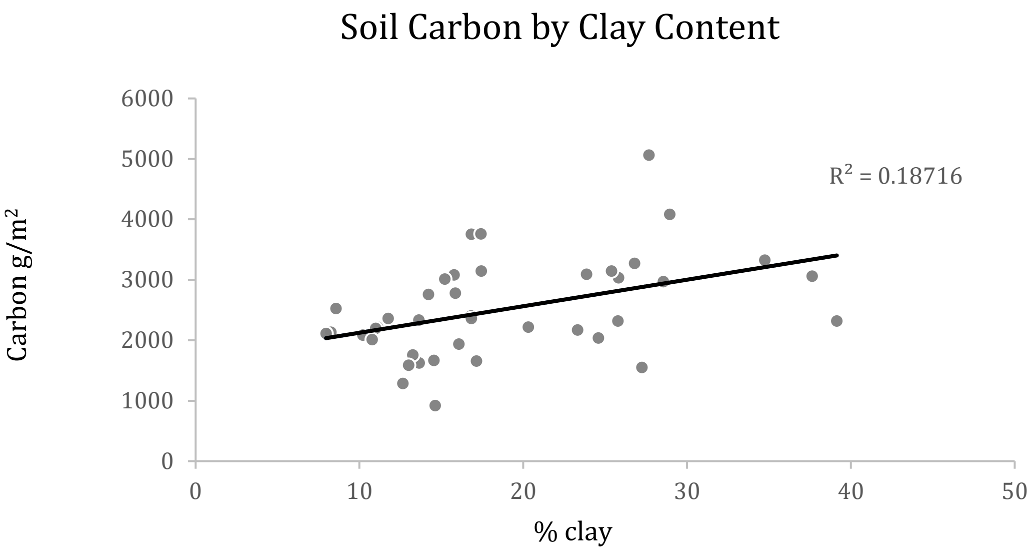

Figure 2. Carbon content (g/m^2) of soil samples versus clay content (%) for all soil samples.

To understand whether climatic variables explain the variation in soil carbon, I modeled the relationship between annual rainfall and soil carbon. For this analysis, three sites (Rush Ranch, Browns Valley, and Mendocino) were excluded from the analysis because suitable climate data near the field site could not be found. Using a simple linear regression model, I found that rainfall correlated with soil organic carbon with an R^2 value of 0.56 ($p<0.01$; Figure 3). I then ran a multiple regression using annual rainfall and clay content as explanatory variables and found that within the multiple regression the relationship between soil carbon and rainfall was significantly positively correlated ($P<0.01$, $R^2=0.58$), but clay content was no longer a significant explanatory variable ($p=0.56$). The least squares linear regression equation, regressing soil C on rainfall, was found to be:

$$C = 25.376x + 1240.3$$

where *C* is soil carbon content, and *x* is annual average rainfall in centimeters. I ran a test on the residuals and found that the data meets the assumptions of a linear regression model.

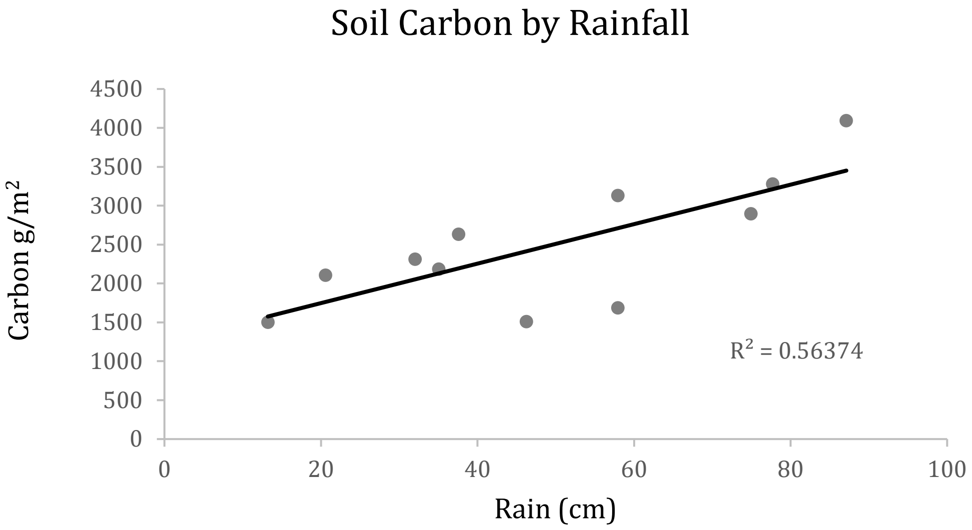

Figure 3. Linear regression between soil carbon (g/m^2) and average annual rainfall (cm).

DISCUSSION

The findings of this study did not support my hypothesis that clay content would correlate strongly with carbon content. While the relationship between clay content and soil carbon was weak, the correlation between average annual rainfall and soil carbon was strong. When regressing clay content and rainfall on soil organic carbon, clay content was found to not be a significant explanatory variable. Clay content is not a good proxy for estimating soil carbon in the California grasslands studied here, and the results of my study highlight the site specificity of soil carbon sequestration.

Soil texture and soil carbon

Soil texture and carbon were found to be positively correlated in this study. This finding is supported in the literature, but the degree of correlation varies. Nichols (1984) found clay content and precipitation correlated strongly with soil carbon (R^2=0.86) and Jobbágy and

Jackson (2000) found that vegetation, precipitation and clay content strongly correlated with carbon sequestration, whereas this study found a weak correlation (R^2=0.19).

Many other studies also found a weak correlation between soil texture and soil carbon; Tan et al. (2004) found that texture was not an important factor in determining carbon in the top 10 cm of soil, and Percival et al. (2000) found that clay content was a poor determining factor of carbon sequestration in soil. Looking more closely at all these studies I found that Nichols (1984) study took place in the Great Plains, a vastly different ecosystem from California, and that Jobbágy and Jackson (2000) who had a US-wide dataset, only found a strong correlation in the deepest layers of the soil, and an R^2=0.07 at the 0-20cm depth. Percival et al. (2000) found a weak trend, similar to that found in this study, and using a New Zealand-wide database. It appears that soil chemistry is less important in certain ecosystems and over a wide range, but can be a strong determining factor on a relatively small scale of nearly heterogeneous grasslands not strongly limited by rainfall.

Influence of other variables

Although soil texture correlated weakly with carbon, average annual rainfall showed a stronger correlation to SOC in these California field sites (R^2=0.56). In my study sites, factors affecting plant growth were more important in determining soil carbon content than the chemistry of the soil (clay content). Jobbágy and Jackson (2000) noted that soil moisture had a strong correlation to soil carbon, which aligns with the results in this study, since rain directly increases soil moisture. Soil moisture is a point-in-time reading of available water to plants, and average annual rainfall provides an understanding of the total water available to plants over time. Research by Burke et al. (1989) found that precipitation and texture had an important influence on soil carbon. Higher precipitation, especially in water-limited ecosystems, increases plant growth and therefore the rate of carbon movement into the soil (Ryals and Silver 2013). The sites studied in this analysis are all annual California grasslands, whose growthis is strongly limited by rainfall. The results suggest that rainfall correlates with oil organic carbon, because rainfall is the key limiting variable on photosynthesis, which drives C transport into the soil. Once plant growth needs are met and vegetation is exhibiting density-dependent growth, clay content and soil chemistry may become more important determining factors of soil carbon, as seen in the study by Nichols (1984) in the Great Plains.

Limitations and future directions

This study examined the relationship between soil texture, average annual rainfall, and soil carbon, across a set of California grasslands, at a single point in time. Future work should focus on how soil carbon changes over time with respect to changes in rainfall. In our study, we are measuring the current carbon storage in the soil rather than total potential carbon storage; perhaps the correlation would be stronger if we were measuring soils closer to their maximum storage potential, if such a limit exists (Stewart et al. 2007).

To understand what drives soil carbon sequestration on a landscape, we need to monitor that landscape over time and manipulate or control for all the ecosystem variables (Ryals and Silver 2013). The larger project the Silver lab is conducting to determine the change in soil organic carbon with compost application will provide insight on how carbon changes over time with increased soil fertility. An open question for further research would consider understanding where carbon sequestration is strongly controlled by plant growth and increased productivity and where it is also affected by soil chemical properties.

Broader implications

Understanding carbon distribution and movement is essential in mitigating climate change. It is necessary to actively remove carbon dioxide from the atmosphere, and to do that we need an understanding carbon movement (Conant et al. 2001). A predictive equation in the amount of carbon a soil can hold or sequester would not only be valuable in understanding how ecosystems sequester carbon, but also be useful for creating policy. A reliable process of calculating soil carbon sequestration potential could set the basis for a system of carbon credits for rangeland managers. Often, rangeland managers are uninterested in implementing management changes without direct benefits, so it is important to create a system whereby they can be rewarded accordingly for the environmental benefits they provide. Management practices that restore or preserve soil carbon not only increase soil fertility and therefore rangeland productivity, but also have the potential to offset some impacts of climate change (Ryals et al. 2014). Widespread active carbon sequestration has the possibility to lower the average global temperature (Lal 2004, Minasny et al. 2016) and it is imperative that we explore and understand this possibility.

ACKNOWLEDGEMENTS

First and foremost, thanks to Sintana Vergara for endless hours of mentorship and editing. Thanks also to Dylan Chapple, Patina Mendez and Kurt Spreyer for thesis-writing guidance. Thanks to Reina Carissa, Eva Malis, Alexander Goetz and Allie Lalor who peer-edited many drafts of this thesis. Everlasting gratitude to Summer Ahmed and Heather Dang for helping me through all the technicalities of the lab work. Without Jeff Borum, John Wick, and Whendee Silver this project would not have been possible and I'm grateful to have been a part of it. Cheers to Nightvale radio, Moth radio hour, and Radiolab for providing endless hours of entertainment while repeatedly measuring out 25mg of soil. And finally, thanks to my parents for supporting me in doing what I love.

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APPENDIX A: Site Descriptions

#	Site name	Site notes	Site Description					
			County	MLRA	Vegetation	Management	Average Rainfall (in)	Average July Temp (°F)
1	Yolo Ranch #2	Baseline data from Beardsley et al.	Yolo	17	Oak woodlands, perennial and annual grasses	Cow-calf grazing, managed to encourage perennial grasses	22.8	77.9
2	Yolo Ranch #1	Severe Medusahead, some NRI-type plots established	Yolo	15	Annual grasses and other invasive species	Sheep grazed, very short duration seasonal	22.8	77.9
3	TK Ranch	Dryland farming for several decades	Alameda	15	Annual grasses	Grazed by horses sporadically	14.8	72.0
4	CC Delta	Slight difficulties with soil type homogeneity and/or anomalies in plot	Contra Costa	16	Annual grasses	Grazed heavily historically	NA	74.4
5	O. Ranch	Low accessibility for future field days	Stanislaus	17	Annual grasses, no natives	Cow-calf, some stockers	13.8	77.3
6	C. Ranch	Plot size altered to avoid potential soil delineations	Santa Barbara	20	Mostly annual grasses	Cow-calf, some stockers	8.1	74.7
7	EA Ranch	Slope >5% in some areas of plot, but runoff has been accounted for	San Diego	20	Mostly annual grasses with small patches of natives near low points	Newly purchased parcel	5.2	92.1
8	Rush Ranch	Ongoing data collection	Solano	16	Varies	Ecologically-minded rotational grazing	NA	NA
9	SFREC – Browns Valley	Ongoing data collection	Yuba	18	Oak woodland and grass		NA	NA
10	SLT – Sears Pt.	Limited information – first visit on Aug. 12	Sonoma	15	TBD	TBD	30.6	70.9
11	Lockeford PMC	Only site without grazing, but has reps	San Joaquin	17	Farmed for various crops	N/A	18.2	73.8
12	W. Ranch	Ongoing data collection	Marin	4B	Varies		34.3	67.7
14	SRT-Kaweah Oaks Preserve	Has other composting projects funded and in the works	Tulare	17	Mostly annual grasses with sparse natives	Will graze according to our prescription	12.6	79.5